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OCT 81   C R CROWELL   DAAG29-77-G-0202

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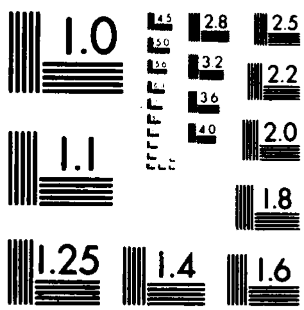

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The major emphasis has been on an experimental study of impact ionization in Pt/nGaAs and Pt/pInP <100> Schottky barrier and developing the theoretical background necessary to interpret the measurements. The intention here was to establish the Schottky barrier as a configuration which would permit more reliable measurements of impact ionization coefficients than p-n junction configurations.

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9. Scientific personnel supported by this project.

   C. R. Crowell

   Chung-Whei Kao - Ph.D. March 1981

   Dennis Lucey

   Min-Wen Chiang

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Work Completed

We have continued work previously carried out under Contract DAHCO-76-6-0002. The major emphasis has been on an experimental study of impact ionization in Pt/nGaAs and Pt/pInP <100> Schottky barrier and developing the theoretical background necessary to interpret the measurements. The intention here was to establish the Schottky barrier as a configuration which would permit more reliable measurements of impact ionization coefficients than p-n junction configurations.

We have completed an analysis of the bias, temperature and quantum energy dependence of photoelectron injection at metal semiconductor interfaces (1), (2) and applied this to measurements on platinum silicide-n type Si Schottky barriers with excellent consistency. The modelling is based upon a minimum of adjustable parameters: the barrier height at zero electric field and the zero temperature extrapolation to the mean free path for optical phonon scattering.

We have revised the thesis work of R. Chwang (3) and improved the representation of a synthesis of his calculations and the results of the Baraff modelling (4). The earlier treatment had some undesirable poles in the curve fitting to the results. We have now established a representation that provides an excellent fit to the data and also permits extrapolation outside the range of the original calculations.

We have applied the above described modelling to the analysis of measurements we have taken on Pt on p type <100>InP. Schottky barriers (5), (6). Aside from obtaining the most reliable measurements to date: they fit breakdown voltage measurements better than any other set of impact ionization measurements, we were also able to show evidence for electric field-dependent average energy for pair production of electrons and holes and a mean free path for hole injection that matched that for the impact ionization characterization

Work in Progress

We have been investigating the effect of band structure on the thresholds for impact ionization in III-V's and observed that contrary to popular expectation, the so called threshold conditions calculated for many III-V's in specific crystal directions are in effect also very close to anti-threshold conditions (oral presentation (2)). We are investigating the effect that the matrix element for the transition will have on the overall impact ionization.

When impact ionization in GaAs was first measured in Schottky barriers, there appeared an unexpected component to photoinjection that was anomalous but was attributed to an anomalous Franz-Keldysh band lowering near the metal. We have never felt that this was so but have investigated the effect of image force on the apparent bandgap lowering for pair production by photoexcitation (oral presentation (5)). Ouroriginal presentation was based upon conservation of momentum only after the excitation. We have revised this treatment to reflect an overall k conservation but wish to sort out a few of the details that still appear anomalous. The conclusion is quite clear, however, that enhanced optical absorption may take place near a Schotkky barrier, but the such low energy pairs are much more likely to be absorbed in the metal rather than result in photoinjection of one of the carriers deeper into the depletion layer.

We have also studied the cascade process initiated by very high energy primaries and deduced the effective threshold energies and phonon energy losses and Fano factors (3). We intend to complete a separate manuscript for publication.

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4. R. Chwang, Chung-Whei Kao and C. R. Crowell, "Normalized Theory of Impact Ionization and Velocity Saturation in Nonpolar Semiconductors via a Marcov Chain Approach", Solid State Electron. 22, 599-620 (1979).
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7. C. R. Crowell, Chung-Whei Kao and R. Chwang, "Band Structure Effect on Threshold Energy and Cross Section for Impact Ionization", manuscript in preparation.

*All except (3) supported by this contract.

Oral Presentations:

1. "Impact Ionization by Electron and Hole in InP and GaAs," by Chung-Whei Kao and C. R. Crowell. Workshop on Hot Electron Phenomena in Semiconductors, Cornell University, August, 1978, also at ARO, Durham, N.C., August, 1978.

2. "Band Structure Effect on Threshold Energy and Cross-Section for Impact Ionization," C. R. Crowell, Chung-Whei Kao and R. Chwang. Workshop on Hot Electron Phenomena in Semiconductors. Cornell University, August, 1978.

3. "A Markov Process Characterization of Impact Ionization," C. R. Crowell and R. Chwang. Workshop on Hot Electron Phenomena in Semiconductors, Cornell University, August, 1978.

4. "Impact Ionization in Semiconductors," Seminar at IBM, Watson Research Lab. Yorktown Heights, NY. August, 1978.

5. "Image Force Effects on Bandgap Lowering for Pair Production Near Metal-Semiconductor Interfaces," C. R. Crowell and Min-Wen Chiang. Presented at PCSI Conf. VII Jan. 1980.

6. "Impact Ionization in InP," C. R. Crowell. Invited Paper presented to the A. V. S., EMPD Division Program, Anaheim, CA March, 1980.

Ref. 2 PHOTOELECTRON INJECTION AT METAL–SEMICONDUCTOR INTERFACES *

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A modelling of the photoinjection process is developed which permits fitting of the spectral photoresponse of Schottky barriers including the electric field dependence of barrier height and photoresponse by means of two adjustable parameters: the zero field barrier $q\phi_{B0}$ and λ_0, the zero temperature mean free path for optical phonon scattering of high energy electrons. The model assumes an image force potential barrier with Thomas–Fermi screening in the metal. Effects of optical phonon scattering and quantum mechanical transmission are convoluted on the Fowler photoelectron supply function. The effects of phonon scattering are frequently large because the ranges in energies associated with the transverse momentum and normal momentum are approximately the amount by which the quantum energy $h\nu$ exceeds the barrier energy $q\phi_B$. At high fields, quantum mechanical tunneling dominates the response when $h\nu < q\phi_B$. At low fields, phonon assisted transmission is appreciable for the same quantum energy range. The calculation of the collection probability includes effects of multiple scattering even for electrons that do not lie initially within the cone of acceptance at the barrier maximum. An approach that considers the probability of collection the same as that of reaching the potential maximum without scattering is found to be acceptable only at high fields. Experimental results are reported from oxide-passivated epitaxial Pt_xSi–⟨111⟩ n-type Si Schottky barrier diodes with annular Schottky barrier guard rings measured at temperatures of 90 and 298 K for an electric field range from 5×10^3 to 9×10^4 V/cm. The field, spectral and temperature dependences of the photoresponse data are in excellent agreement with theoretical predictions with λ_0 = 110 Å at both 90 and 298 K. The zero field barrier height obtained from fitting photoresponse curves at a number of electric fields is also in excellent agreement with I–V and C–V measurements.

Ref. 4 NORMALIZED THEORY OF IMPACT IONIZATION AND VELOCITY SATURATION IN NONPOLAR SEMICONDUCTORS VIA A MARKOV CHAIN APPROACH†

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(*Received* 12 *January* 1977; *in revised form* 13 *February* 1979)

Abstract—This paper presents an investigation of the velocity, energy, and impact ionization distributions in nonpolar semiconductors at very high fields. The treatment uses a finite Markov chain formulation. When optical phonon collisions and impact ionization are the major scattering mechanisms in the semiconductor, a transition matrix which characterizes the transition probabilities between virtual states defined by small discrete energy intervals can be easily computed. The resulting matrix provides the means not only to study the impact ionization phenomenon but also the steady state transport velocity and energy distribution of the charge carriers at high electrical fields and a given lattice temperature. In addition, the effects on the transport properties due to either an abrupt infinite (AI) or a finite energy dependent (FED) ionization cross-section above the ionization threshold energy are examined. The calculated avalanche transport velocity shows excellent agreement with the experimental data in Si obtained by Duh and Moll. The resulting calculations when extrapolated to a lower field also agree favorably with existing saturation drift velocity data in n and p type Si and p type Ge. The energy distribution is shown to be strongly affected by the choice of the model for the energy dependence of the ionization cross-section. One of the main applications of the results is to assist investigation of the non-localized nature of electron and hole avalanche ionization coefficients previously noted by Okuto and Crowell (O–C). The present results for this spatial distribution can replace O–C's intuitively chosen exponential approximation. The spatial ionization distribution generated by the present calculation is essentially exponential with a threshold energy dark space. This result provides a useful kernel for a more precise formulation in studies that relate impact ionization coefficients to charge multiplication data. The normalized ionization coefficients obtained from the AI model are very similar to Baraff's calculation as are the FED model results after appropriate normalization. Simple analytical expressions with meaningful asymptotic results for the average ionization energy and the ionization coefficient are also derived from the present data. These results are applicable for a range of different energy dependence of the ionization cross section provided that the average energy for pair production is used as the effective threshold parameter.

Ref. 5

IMPACT IONIZATION BY ELECTRONS AND HOLES IN InP†

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(*Received 6 August 1979; in revised form 3 November 1979*)

Abstract— Ionization coefficients of holes in InP exceed those of electrons by a factor of approximately four over the electric field range from 2.5 to 4.5×10^5 V/cm and have been measured in Pt on *p*-type (100) orientation InP Schottky diodes. The shape of the baseline for the hole induced multiplication has been fitted by using one adjustable parameter, namely: the mean free path for optical phonon scattering. The model includes effects of quantum mechanical transmission, barrier height lowering and phonon scattering before the barrier maximum. The shape of the baseline for electron multiplication was likewise fitted by one adjustable parameter: the minority carrier diffusion length. Both models produce an excellent fit to low field characteristics that have appreciable curvature. The average phonon scattering mean free path for holes is ~35 Å roughly consistent with that required to characterize the hole ionization coefficient. The electron diffusion length in *p*-type InP was found to be ~ 18 μ for all diodes. Ionization coefficients were obtained for diodes in the doping range from 5.0×10^{15} to 7.8×10^{15} cm^{-3}. The impact ionization curves were fitted by Baraff-Chwang curves with slightly field dependent average energies for pair production. The threshold energies have been calculated from a consideration of energy and momentum conservation in a theoretical band structure. The deduced mean free paths for phonon scattering and breakdown voltages calculated from the ionization coefficient measurements are in excellent agreement with other independent experiments.

Ref. 6

Chung-Whei Kao

Abstract of Ph.D

DISSERTATION

PHOTOINJECTION AND CURRENT MULTIPLICATION AT METAL-SEMICONDUCTOR INTERFACES

Impact ionization coefficients of holes in Indium Phosphide exceeding those of electrons by a factor of approximately four over the electric field range from 2.5 to 4.5×10^5v/cm have been measured in Pt on p-type <100> orientation InP Schottky diodes.

In study of the majority carrier injection baseline, a modelling of the photoinjection process is developed which permits fitting simultaneously the electric field dependent, temperature dependent and spectral dependent photoresponse curves with a minimum number of adjustable parameters. The model assumes an image force potential barrier with Thomas-Fermi screening in the metal. Effects of phonon scattering and quantum mechanical transmission are convoluted on the Fowler photoelectron supply function. Comparison of the collection probabilities for single phonon scattering and multi-phonon scattering are presented. It was found that at low field the effect of phonon assisted transmission on the photoresponse is appreciable for $h\nu > q\phi_B$. At high field, quantum mechanical tunneling dominates the response and effect of multiphonon scattering becomes insignificant for the same quantum energy range.

The shape of the baseline for the majority carrier induced multiplication has been fitted by using one adjustable parameter, namely: the mean free path for phonon scattering. The shape of the baseline for minority carrier induced multiplication was likewise fitted by one adjustable parameter: the minority carrier diffusion length. Both models produce an excellent fit to low field characteristics that have appreciable curvature. The average phonon scattering mean free path for holes is ≃ 35 Å, roughly consistent with that required to characterize the hole ionization coefficient. The electron diffusion length in p-type InP was found to be ≈18μm for all diodes. Impact ionization curves were fitted by Baraff-Chwang curves with slightly field dependent average energies for pair production. The threshold energies have been calculated from a consideration of energy and momentum conservation in a theoretical band structure. The deduced mean free path for phonon scattering and breakdown voltages calculated from the ionization coefficient measurements are in excellent agreement with other independent experiments.

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